

Accretion Flows in X-ray Binaries

BY CHRIS DONE

*Department of Physics, University of Durham, South Road, Durham DH1 3LE,
UK*

I review the X-ray observations of Galactic accreting black holes and neutron stars, and interpretations of these in terms of solutions of the accretion flow equations.

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1. Introduction

One of the key puzzles in X-ray astronomy is to understand accretion flows in a strong gravitational field. This applies to both Active Galactic Nuclei (AGN) and Quasars, where the accretion is onto a supermassive black hole, and to the stellar mass Galactic black holes (GBH) and even the neutron star systems. Neutron star radii are of order three Schwarzschild radii, i.e. the same as that for the last stable orbit of material around a black hole. Thus they have very similar gravitational potentials so should have very similar accretion flows, though of course with the major difference that neutron stars then have a solid surface, so can have a boundary layer and a stellar magnetic field.

The main premise throughout this paper is that progress in understanding accretion in *any* of these objects should give us some pointers to understanding accretion in *all* of them. Galactic sources are intrinsically less luminous, but a great deal closer than the AGN, so generally are much brighter. The variability timescales also scale with the mass of the central object so it is much easier to study *changes* in the accretion flow onto Galactic sources. Thus we can use the Galactic sources as a laboratory for understanding accretion processes, and then see how much of this can be transferred to AGN.

2. Instabilities in Accretion Flows

Accretion onto a black hole via an optically thick disk has been known for decades to produce rather robust spectral predictions (Shakura & Sunyaev 1973; hereafter SS). The emission should consist of a sum of quasi-blackbody spectra, peaking at a maximum temperature of ~ 0.6 keV for accretion rates around Eddington onto a $\sim 10M_{\odot}$ GBH, or at ~ 0.3 keV for accretion rates at ~ 1 per cent of Eddington. The whole accretion disk structure is determined mainly by the luminosity (i.e. mass accretion rate) as a fraction of the Eddington luminosity, \dot{m} , and is only weakly dependent on the mass of the black hole.

However, these steady state accretion disk solutions are generically unstable. At low mass accretion rates then the point at which hydrogen makes the transition between being mostly neutral to mostly ionised gives a dramatic instability. When

a part of the disk starts to reach temperatures at which the Wien photons can ionise hydrogen then these photons are absorbed. This energy no longer escape from the disk, so it heats up, which produces higher temperatures and more photons which can ionise hydrogen, so more absorption and still higher temperatures. The runaway heating only stops when hydrogen is mostly ionised.

If the temperature crosses the hydrogen ionisation instability point at *any* radius in the disk then the *whole disk* is unstable. This classic disk instability (DIM) is responsible for a huge variety of variability behaviour. In the neutron stars and black holes the DIM is made more complex by X-ray irradiation: the outburst is triggered by the DIM, then irradiation contributes to the ionisation of hydrogen, so controls the evolution of the disk, while it can also enhance the mass transfer from the companion star (e.g. the review by Lasota 2001).

There may also be a further instability at high mass accretion rates, where the pressure in the disk is dominated by radiation. If the heating rate scales with the total pressure, then this scales as T^4 where radiation pressure dominates. A small increase in temperature leads to a large increase in heating rate, and so to a bigger increase in temperature. The runaway heating only stabilises when the timescale for the radiation to diffuse out of the disk is longer than the accretion timescale for it to be swallowed by the black hole (optically thick advection: Abramowicz et al. 1988). The spectrum of these slim disks are slightly different to those of standard SS disks, as the energy generated in the innermost orbits is preferentially advected rather than radiated (Watarai & Mineshige 2002). At these high mass accretion rates the disk can also overheat, causing the inner disk to become strongly comptonised (Shakura & Sunyaev 1973; Beloborodov 1998).

However, there is much uncertainty about the disk structure at such high mass accretion rates. The association of the viscosity with the magnetic dynamo means that the viscous heating may scale only with the gas pressure, rather than the total pressure, which removes the radiation pressure instability (Stella & Rosner 1984). Even the advective cooling may be circumvented if the disk becomes clumpy, so that the disk material is not as efficient in trapping the radiation (Turner et al., 2002; Gammie 1998; Krolik 1998).

Figure 1a shows the equilibrium solutions (i.e. places where heating balances cooling) of an SS disk at a given radius and viscosity. The disk surface density, $\Sigma = \int \rho dz \propto \tau$, where τ is the optical depth of the disk, generally increases as the mass accretion rate increases, but the hydrogen ionisation and radiation pressure instabilities are so strong that the disk surface density actually decreases at these points. The dotted line shows where the disk behaviour becomes very uncertain.

3. Observations of Accretion Flows in Galactic Black Holes

Most black hole binaries are in systems where the outer edge of the disk is cool enough to dip below the hydrogen ionisation point. They are generically transient, and show large variability. These give us a sequence of spectra at differing mass accretion rates onto the central object, allowing us to test accretion models.

What is seen is generally very different to the simple Shakura-Sunyaev disk emission ideas outlined above. At high mass accretion rates (approaching Eddington) the spectra are dominated by a soft component at $kT \sim 1$ keV which is strongly (very high state: VHS) or weakly (high state: HS) Comptonized by low

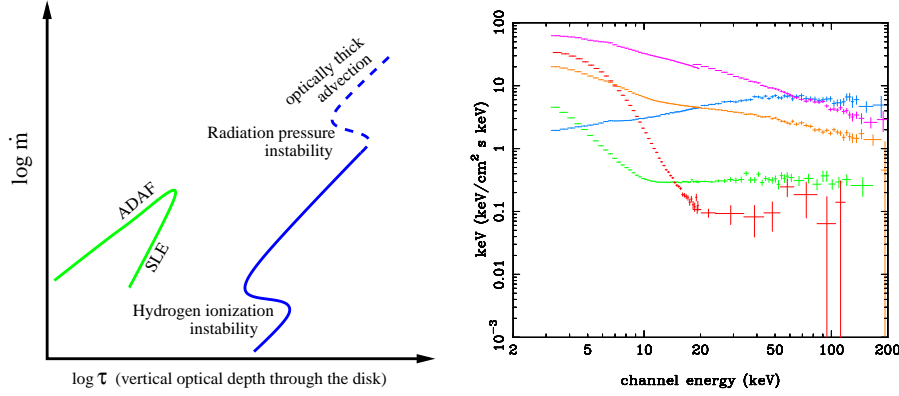


Figure 1. (a) The multiple solutions to the accretion flow equations. The right hand line is the Shakura-Sunyaev disk, modified by advective cooling at the highest mass accretion rates, and by atomic opacities at the lowest mass accretion rates. The left hand line is the optically thin flows, the advective flows (ADAF) and Shapiro-Lightman-Eardley (SLE) solutions. (b) RXTE PCA and HEXTE data from RXTE J1550-564 showing the Low state (peaking at 100 keV), and a variety of high mass accretion rate spectra, all of which peak at ~ 1 keV. There is the high state (disk sharply peaking at 1 keV), ultrasoft spectrum (disk showing rounded peak at 1 keV) and two high states (disk strongly comptonised to give a smooth, steep spectrum).

temperature thermal (or quasi-thermal) electrons with $kT \sim 5 - 20$ keV (Zycki et al., 1998; Gierlinski et al., 1999; Kubota et al., 2001). There is also a rather steep power law tail ($\Gamma \sim 2 - 3$) which extends out beyond 511 keV in the few objects with good high energy data (e.g. Grove et al., 1998). At lower mass accretion rates, below $\sim 2 - 3$ per cent of Eddington, there is a rather abrupt transition when the soft component drops in temperature and luminosity. Instead this (low state: LS) spectrum is dominated by thermal Comptonization, with $\Gamma < 1.9$, rolling over at energies of ~ 150 keV (see e.g. the reviews by Tanaka & Lewin 1995; van der Klis 1995; Nowak 1995). This spectral form seems to continue even down to very low luminosities (~ 0.01 per cent of Eddington: the quiescent or off state e.g. Kong et al. 2000). Figure 1b shows a selection of VHS, HS and LS spectra from the GBH transient RXTE J1550-564.

While XMM-Newton and Chandra have opened up new windows in high resolution X-ray imaging and spectroscopy, RXTE gives an unprecedented volume of data on these sources. To get a broad idea of the range of spectral states then quantity as well as quality is important! But this also means that plotting individual spectra is too time consuming. Colour-colour and colour-intensity diagrams have long been used in neutron star X-ray binaries to get an overview of source behavior. The problem is that they often depend on the instrument response (counts within a certain energy range) and on the absorbing column towards the source. To get a measure of the source behaviour we want to plot *intrinsic* colour, i.e. unabsorbed flux ratios over a given energy band. To do this we need a physical model. Plainly there can be emission from an accretion disk, together with a higher energy component from comptonisation. Reflection of this emission from the surface of the accretion disk can also contribute to the spectrum. Thus we use a model consisting of a multicolour accretion disk, comptonised emission (which is *not* a power law

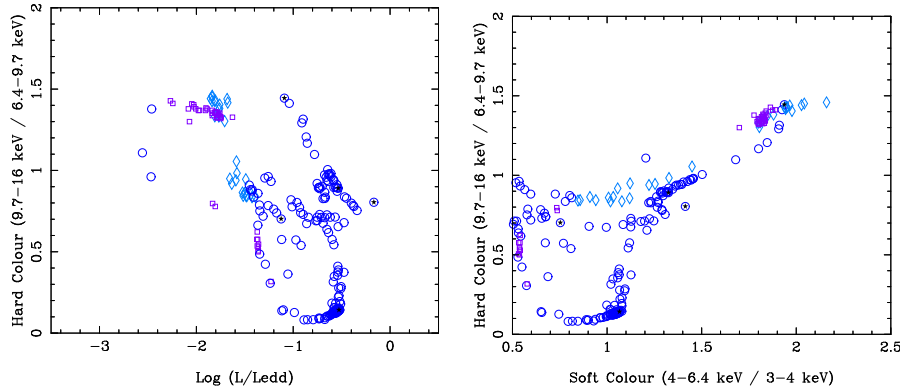


Figure 2. Luminosity-colour and colour-colour plots for the RXTE PCA data on the Galactic black holes GX339 (squares), Cyg X-1 (diamonds) and J1550-564 (circles). Points corresponding to the spectra in Figure 1b are marked with stars.

at energies close to either the seed photon temperature or the mean electron energy), with gaussian line and smeared edge to roughly model the reflected spectral features, with galactic absorption.

We use this model to fit the RXTE PCA data from several different black holes from archival RXTE data to follow their broad band spectral evolution. We choose 4 energy bands, 3-4 keV, 4-6.4 keV, 6.4-9.7 keV and 9.7-16 keV, and integrate the unabsorbed model over these ranges to form *intrinsic* colours and use the generally fairly well known distance to convert the extrapolated bolometric flux to total luminosity. Again, since the mass of the central object is fairly well known we can translate the bolometric luminosity into a fraction of the Eddington luminosity.

Figure 2a shows a hard colour versus luminosity plot for the black holes Cyg X-1 (diamonds), GX339-4 (squares) and J1550-564 (circles). The general trend is spectra with $L/L_{Edd} < 0.03$ to be hard while those at higher luminosities are soft. The hard spectra from J1550-564 at 10 per cent of Eddington are from the extremely rapid *rise* to outburst (see Wilson & Done 2001) where the accretion flow was presumably far from steady state. Apart from this, it is clear that there is a transition from hard to soft spectra at a few per cent of Eddington.

The huge range in spectral behaviour is brought out more clearly on a colour-colour plot (Figure 2b). The hardest spectra (low/hard state) form a well defined diagonal track, where hard and soft colour change together while the soft spectra show an amazing variety of shapes. The points corresponding to the spectra in figure 1b are (2,1.5) for the low/hard, (0.7,0.7) for the high state, (1.4,0.8) for the VHS and (1,0.1) for the ultrasoft spectrum.

4. Observations of Accretion Flows around Neutron stars

Neutron stars without a strong magnetic field ($B < 10^{12}$ G) come in two flavors, named atolls and Z sources. Z sources are named after a Z-shaped track they produce on an X-ray colour-colour diagram, while atolls are named after their C (or atoll) shaped track. These differences between the two LMXBs categories probably reflect differences in both mass accretion rate, \dot{M} , and magnetic field, B , with the Z sources having high luminosity (typically more than 50 per cent of the Edding-

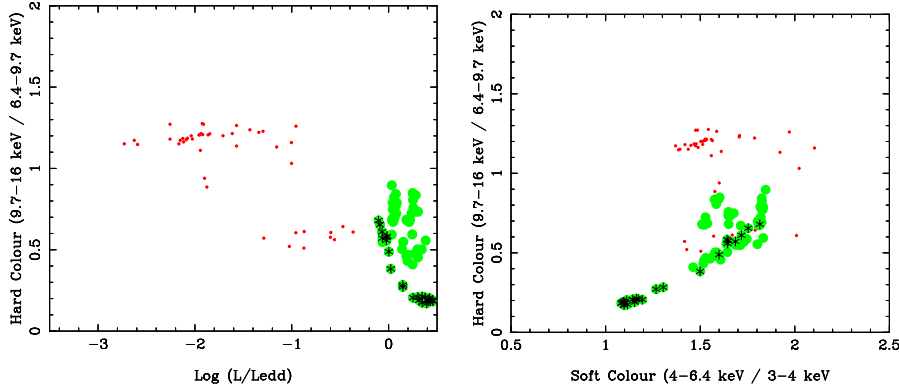


Figure 3. Luminosity-colour and colour-colour plots for the RXTE PCA data on the transient atolls (low magnetic field disk accreting neutron stars - small dots). Again there is a hard to soft spectral switch at ~ 10 per cent of Eddington. The standard Z sources Cyg X-2, Sco X-1 and GX 17+2 are shown as large circles, while stars show Cir X-1.

ton limit) and magnetic field ($B \geq 10^9$ G) while the atolls have lower luminosity (generally less than 10 per cent of Eddington) and low magnetic field ($B \ll 10^9$ G) (Hasinger & van der Klis 1989).

Most of these are *stable* to the disk instability (neutron stars round the same mass companion need to be closer than a black hole for the star to fill its Roche lobe. The disk is smaller, and hotter so less likely to trigger the hydrogen ionisation instability: King & Ritter 1998). However, there are a few (probably evolved) atoll systems which are transient, Figure 3a shows the colour-luminosity plot for these systems (small filled circles), while figure 3b shows their colour-colour diagram. Plainly there is again a switch from a well defined hard state to a softer spectrum at ~ 10 % of Eddington, although here the soft state also forms a single well defined track. Because these are *intrinsic* colours, this diagram can be overlaid on that for the black holes. It is clear that the neutron star spectra evolve in very different ways with mass accretion rate, and that the softest black hole spectra (high state and ultrasoft) are not seen in these atoll sources.

However, the 'ultrasoft' spectrum is not a unique black hole signature as the odd neutron star binary Cir X-1 (tentatively classed as a Z source) has been known for a long time to show such a spectrum. Figures 3a and b also include data from Cir X-1 (stars) and standard Z sources (large filled circles). It is immediately clear that the standard Z sources do not vary by much from Eddington and that their spectral variability along their Z is rather small also (the Z track in figure 3b is mostly masked by the symbol size!). And while Cir X-1 is not convincingly like either class of system, the important point here is that Cir X-1 certainly ends up at the same 'ultrasoft' spectrum as the black holes on a colour-colour diagram. Perhaps when the mass accretion rate is extremely high then the flow is so optically and geometrically thick that it completely swamps the central object, so that the nature of the central object becomes unimportant. However, *no* neutron star systems show the high state spectra. These may be a unique black hole signature, as the boundary layer which should always be present in the neutron stars will provide a higher temperature (harder) component, unless the flow is so thick that it completely buries the central object.

5. X-ray emission in the low/hard state

Hard X-rays are a generic feature of accretion onto a black hole in all spectral states, yet the standard SS disk models cannot produce such emission. Even worse, the observations show that we have to explain different sorts of hard X-ray emission, with a fairly well defined spectral switch between the hard and soft spectra at luminosities of around 3 per cent of Eddington. This mechanism has to work also in the low magnetic field neutron stars at low mass accretion rates.

To get hard X-rays then a large fraction of the gravitational energy released by accretion must be dissipated in an optically thin environment where it does not thermalise, and so is able to reach much higher temperatures. For the SS disk, an obvious candidate is that there are magnetic flares above the disk, generated by the Balbus–Hawley MHD dynamo responsible for the disk viscosity (Balbus & Hawley 1991). Buoyancy could cause the magnetic field loops to rise up to the surface of the disk, so they can reconnect in regions of fairly low particle density. This must be happening at some level, and is shown by numerical simulations, but current models (although these are highly incomplete as in general the simulated disks are not radiative) do not carry enough power out from the disk to reproduce the observed low/hard state (Miller & Stone 2000).

If such mechanisms produce the low state spectra, then we also need a mechanism for the transition. The obvious candidate is the radiation pressure instability. However, the disk is no longer a standard SS disk as much of the power is dissipated in a magnetic corona rather than in the optically thick disk. The disk is cooler and denser (Svensson & Zdziarski 1994), which means that it is gas pressure dominated up to higher mass accretion rates than a standard SS disk. The disk just starts to hit the radiation pressure instability at a few per cent of Eddington when the fraction of power dissipated in the corona is around 60 per cent, but in the limit where all the power is dissipated in the corona then the disk is *stable* at all mass accretion rates below the Eddington limit (Svensson & Zdziarski 1994).

An alternative to the SS disk models is that the inner disk is replaced by an optically thin, X-ray hot accretion flow. This flow still has to dissipate angular momentum, so magnetic reconnection is still the source of heating, but the assumption here is that the accretion energy is given mainly to the protons, and that the electrons are only heated via Coulomb collisions. The proton temperature approaches the virial temperature so pressure support becomes important and the flow is no longer geometrically thin. The electrons cool by radiating, while the protons cool only by Coulomb collisions, so the flow is intrinsically a two temperature plasma. Where the electrons radiate most of the gravitational energy through comptonisation of photons from the outer disk then the solution is that of a Shapiro–Lightman–Eardley (SLE: Shapiro et al 1976) flow, while if the protons carry most of the accretion energy into the black hole then this forms the advection dominated accretion flows (Narayan & Yi 1996). These two solutions are related, as in general both advection and radiative cooling are important (Chen et al 1995, Zdziarski et al 1998). They are sketched as the grey line in Figure 1a. The SLE flows are unstable, although not dramatically so (Zdziarski 1998), while ADAFs are stable (Narayan & Yi 1995).

Importantly, both optically thin flows give typical electron temperatures of ~ 100 keV, as required to explain the low/hard spectra, and both can only exist (in

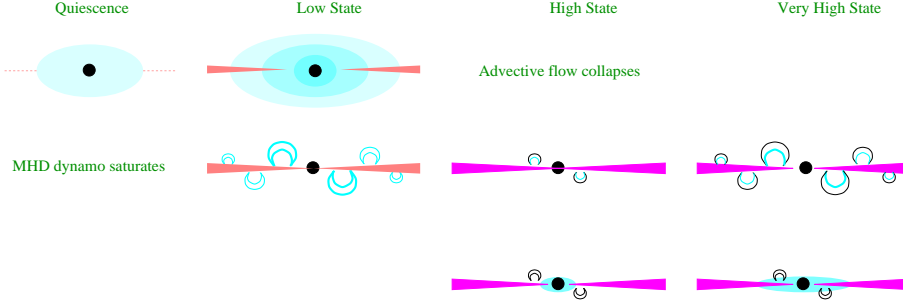


Figure 4. Potential X-ray emission mechanisms in the various spectral states. In quiescence the disk is NOT in steady state (as indicated by the dotted line). Hydrogen is mostly neutral and the MHD dynamo probably cannot operate. In the low state the accretion flow is in (quasi)steady state. Hydrogen is ionised so the MHD dynamo works, and if there is reconnection above the disk then this could heat the electrons. Alternatively, the X-ray emission in both quiescence and low state could be powered by an advective flow. In the high and very high states the only serious contender for the hard power law tail is magnetic reconnection leading to a non-thermal electron distribution (indicated by the black loops), while the thermal electrons could be part of the same mechanism (grey loops) or could be associated with the inner disk.

fact they merge) at mass accretion rates below a critical value of a few per cent of Eddington (Chen et al., 1995) as when the flow becomes optically thick then the Coulomb collisions become efficient so that the flow collapses back into the one temperature SS disk solution. Hence these flows could produce both the quiescent and LS spectra, and the collapse of such flows may give the physical mechanism for the hard-soft state transition (Esin et al., 1997)

6. X-ray emission in the high/soft states

The high mass accretion rate spectra are dominated by the disk emission, but there is always a weak, power law X-ray tail (HS) and sometimes strong comptonisation of the disk emission (VHS). Magnetic reconnection above the disk is really the only known contender for producing the X-ray tail, but here the electrons must have a nonthermal spectrum (Gierlinski et al., 1999). The strong comptonisation of the disk may be connected to this same mechanism, with the electrons partially thermalising to produce a thermal/nonthermal hybrid plasma (Poutanen & Coppi 1998). Alternatively, the comptonisation may be connected to the inner portion of the disk, either overheating in the standard disk equations (SS; Beloborodov 1998), or as a result of trying to change its structure when it reaches the radiation pressure instability (Kubota et al., 2001).

Figure 4 sketches all these potential hard X-ray emission mechanisms.

7. A Unified description of Accretion flows in X-ray binaries

A truncated disk/inner hot flow model can explain the evolution of the different classes of X-ray binaries on a colour-colour and colour-luminosity diagram. For all types of sources we assume that the evolution of the source can be explained if the main parameter driving the spectral evolution is the average mass accretion

rate, \dot{m} . This is *not* the same as the instantaneous mass accretion rate, inferred from the X-ray luminosity. There is some much longer timescale in the system, presumably tied to the response of the disk and/or inner flow (e.g. van der Klis 2000; 2001). While the truncation mechanism is not well understood, it seems likely that conductive heating of a cool disk by the hot plasma (especially if they are magnetically connected) could lead to evaporation of the disk (Meyer & Meyer-Hofmeister 1994; Rozanska & Czerny 2000), so that there is a smooth transition from an outer disk to inner hot flow.

A qualitative picture could be as follows, starting at low \dot{m} . For the black holes, as \dot{m} increases then the truncation radius of the disk decreases, so it penetrates further into the hot flow. The changing geometry gives more soft photons to cool the hot flow, and so leads to softer spectra. Both hard and soft colours soften together as the power law produced by Compton scattering in the inner flow is still the only component within the PCA bandpass. Then the inner flow reaches its maximum luminosity, and collapses. As the inner disk replaces the hot flow then the disk is close enough to contribute to the spectrum above 3 keV, so the soft colour abruptly softens. The hard X-ray tail is produced by the small fraction of magnetic reconnection which takes place outside of the optically thick disk (high state). At even higher \dot{m} then the disk structure is not well understood, but there seems to be a choice of two disk states, one in which the inner disk emission is strongly Comptonised (very high state), characterised by moderate hard and soft colours or else is extremely disk dominated, as characterised by very soft hard colours.

The atoll neutron stars show similar evolution, except that they also have a solid surface and so have a boundary layer. At low \dot{m} then the disk is truncated a long way from the neutron star, and the boundary layer is mostly optically thin, so it joins smoothly onto the emission from the inner accretion flow. Reprocessed photons from the X-ray illuminated surface form the seed photons for Compton cooling of the inner flow. As \dot{m} increases, the disk starts to move inward, but the cooling is dominated by seed photons from the neutron star rather than from the disk, so the geometry and hence the high energy spectral shape does not change. The atolls keep constant hard colour, but the soft colour softens as the seed photon energy moves into the PCA band. The inner flow/boundary layer reaches its maximum luminosity when it becomes optically thick. This causes the hard colour to soften as the cooling is much more effective as the boundary layer thermalises, so its temperature drops. The disk replaces the inner hot flow, so the disk temperature starts to contribute to the PCA bandpass so the soft colour softens abruptly. The track moves abruptly down and to the left during this transition. After this then increasing \dot{m} increases the disk temperature, so the motion is to higher soft colour (Gierlinski & Done 2002a; 2002b). The 'banana state' is then analogous to the high/soft state in the galactic black holes, but with additional luminosity from the boundary layer.

The Z sources can be similar to the atolls, but with the addition of a magnetic field (Hasinger & van der Klis 1989). In general they are stable to the disk instability because of the high mass accretion rates, so vary only within a factor of 2. The disk evaporation efficiency decreases as a function of increasing mass accretion rate, so this cannot truncate the disk in the Z sources. Instead the truncation is likely to be caused by stronger magnetic field, but here the increased mass accretion rate means that the inner flow/boundary layer is already optically thick, and so cooler (Gierlinski & Done 2002a).

Models with a moving inner disk radius at low mass accretion rates also can qualitatively explain the variability power spectra of these sources. They show characteristic frequencies in the form both of breaks and Quasi Periodic Oscillations (QPO's). These features are related ($f_{break} \sim 10f_{QPO}$ for the low frequency QPO), and they *move*, with the frequencies generally being higher (indicating smaller size scales) at higher \dot{m} (see e.g. the review by van der Klis 2000). Recent progress has concentrated on the similarity between the relationship between the QPO and break frequencies in black holes *and* neutron star systems (e.g. the review by van der Klis 2000). If they truly are the same phenomena then the mechanism *must* be connected to the accretion disk properties and not to the magnetosphere or surface of the neutron star. While the variability is not yet understood in detail, *all* QPO and break frequency models use a sharp transition in the accretion disk in some form to pick out a preferred timescale (e.g. van der Klis 2000), so by far the easiest way to change these frequencies is to change the inner disk radius.

8. Observational tests of the Low/hard state geometry

While disk truncation with an inner X-ray hot flow can form a coherent picture for the low mass accretion rate X-ray binaries and Z sources, there is the alternative model in which the low state is produced by magnetic flares above an untruncated disk. This is a very different geometry to that of a truncated disk, so there should be some testable, observational signatures of the inner disk which can enable us to discriminate between these two models.

(a) *Direct disk emission*

The most direct way to see whether there is an inner disk is look at the disk emission. The SS disk models make clear predictions about the temperature and luminosity of the disk, and these can easily be modified for the case where some fraction f of the energy is dissipated above and below the disk (Svensson & Zdziarski 1994). Both disk temperature, and luminosity, and fraction of energy emitted in the corona can be *observed* with a broad band spectrum showing both disk and hard X-ray emission, so the disk inner radius can be constrained directly from the data.

However, the expected temperatures for disks around black holes accreting at a few per cent of Eddington are in the EUV/soft X-ray region where interstellar absorption is important. Most black holes and neutron stars are in the galactic plane, so there is high obscuration. ASCA and SAX observations of Cyg X-1 in the low/hard state infer disk temperatures of ~ 0.1 keV (di Salvo et al., 2001), while the broad band SAX spectrum also shows its total bolometric luminosity was about 2 per cent of Eddington, with 70 per cent of this emitted in the hard X-ray spectrum (di Salvo et al., 2001). Both energetics and disk temperature are consistent with a disk truncated at about 50 Rs, but an untruncated disk with 70 per cent of the power dissipated above the optically thick disk material has a temperature of ~ 0.2 keV. This is marginally inconsistent with that observed, but not dramatically so, and the absorption to Cyg X-1 is fairly high so there are some systematic uncertainties.

The disk is much more clearly seen in the transient black hole system RXTE J1118+480. This has extremely low galactic absorption, so the disk emission can be

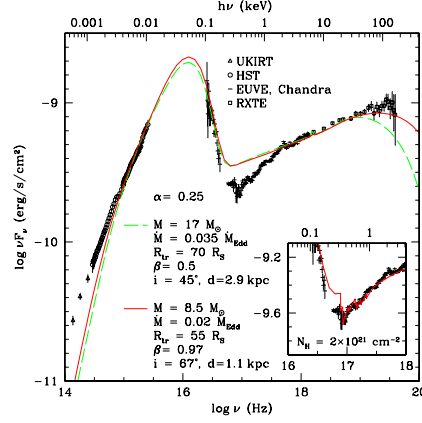


Figure 5. The multiwavelength broad band spectrum of the black hole transient RXTE J1118+480, from Esin et al., (2001). The low galactic column to this source means the direct disk emission can easily be observed with HST and EUVE.

detected with HST and EUVE. The temperature is ~ 0.02 keV, while the luminosity is again a few per cent of Eddington, with about 40 per cent of the total emitted in hard X-rays. This low disk temperature is completely inconsistent with a disk extending down to the last stable orbit (McClintock et al. 2001), even with 90 per cent of the power dissipated in a hot corona. Esin et al., (2001) successfully fit the overall spectral shape with a truncated disk/inner advective flow model (Figure 5).

(b) Reflection

An independent way to study the extent of the optically thick accretion flow is via reflection. Wherever hard X-rays illuminate optically thick material then there is some probability that the X-rays can be reflected. The reflection probability is given by a trade-off between the importance of electron scattering and photo-electric absorption. Since the latter is energy dependent, the albedo is also energy dependent, with higher energy photons being preferentially reflected due to the smaller photo-electric opacity of the material. This gives rise to a reflected spectrum that is harder than the intrinsic spectrum, with photo-electric edge features, and associated fluorescent lines imprinted on it. Since iron is the highest atomic number element which is astrophysically abundant, the iron K edge is particularly prominent, at 7.1–9.3 keV depending on the ionization state of the reflecting material, together with its associated iron K α fluorescence line emission at 6.4–6.9 keV (see e.g. the review by Fabian et al., 2000).

The reflected spectrum (line and continuum) is smeared by special and general relativistic effects of the motion of the disk in the deep gravitational potential well (Fabian et al., 1989; Fabian et al 2001). The fraction of the incident flux which is reflected gives a measure of the solid angle of the optically thick disk as observed from the hard X-ray source, while the amount of smearing shows how far the material extends into the gravitational potential of the black hole. This should give a clear test of whether the inner disk is present.

The Galactic Black holes in the low/hard state show overwhelmingly that the solid angle is significantly less than 2π , and that the smearing is less than expected

for a disk extending down to the last stable orbit (Zycki et al., 1997; 1998; 1999; Gierlinski et al., 1997; Done & Zycki 1999; Zdziarski et al., 1999; Gilfanov et al., 1999; Revnivtsev et al., 2000). While this is clearly consistent with the idea that the disk is truncated in the low/hard state, an alternative explanation for the lack of reflection and smearing is that the inner disk or top layer of the inner disk is completely ionised. There are then no atomic features, and the disk reflection is unobservable in the 2–20 keV range as it appears instead to be part of the power law continuum (Ross & Fabian 1993; Ross et al., 1999; Nayakshin et al 2000). Ionisation could be especially important in GBH due to the high disk temperature predicted by SS untruncated disk models, and indeed in the HS and VHS the reflection signature from the disk in GBH is clearly ionised (Gierlinski et al., 1999; Wilson & Done 2001; Miller et al., 2001). However, for the low/hard state, the *observed* disk temperatures of less than 0.1 keV are not sufficient to strongly ionise iron. Collisional ionisation does not strongly distort the GBH reflection, but photo-ionisation can be very important, and models with complex photo-ionisation structure can fit the observed reflection signature by an untruncated disk (Young et al 2001; Done & Nayakshin 2001; Ballantyne et al., 2001). However, the inner disk in such models is not completely invisible as the illuminating photons at ~ 100 keV cannot be reflected elastically. They heat the disk due to Compton downscattering, so it reprocesses and thermalises the hard X-rays down to temperatures which are typically of order of the temperature expected from a Shakura-Sunyaev inner disk or higher. While detailed models of the thermalised emission from complex ionisation models have not yet been fit to the data, at least 20 per cent of the illuminating flux should be thermalised by the inner disk, leading to a higher temperature than observed in RXTE J1118+480.

Reflection and reprocessed, thermal emission from the disk can be suppressed entirely if the magnetic flares are expanding relativistically away from the disk (Beloborodov 1999). However, the disk emission in RXTE J1118+480 and Cyg X-1 would then have to be the intrinsic disk emission, and the expected temperature the observed luminosity with an untruncated disk is again higher than those observed.

9. Conclusions

A truncated disk at low mass accretion rates is compatible with *all* the constraints on the extent of the accretion disk as measured by direct emission and reflection. It can also give a unified picture of the evolution of the broad band spectral shape in both accreting black holes and neutron stars, and qualitatively explain the variability power spectra if the disk extends further into the gravitational potential as the mass accretion rate increases. The most convincing single measurement which challenges alternative, untruncated disk models for the low/hard state is the observed low temperature disk in the black hole transient RXTE J1118-480, with supporting evidence for a low disk temperature in Cyg X-1. Evaporation of the disk into a hot inner accretion flow gives a plausible physical mechanism for the truncation, and the mass accretion rate at which the inner flow becomes optically thick gives a mechanism for the spectral switch from hard to soft spectra. At higher mass accretion rates the structure of the accretion disk is not well understood, and the data seem to show a variety of soft spectral shapes which may be associated

with optically thick advection (slim disks) and/or the radiation pressure instability and/or overheating of the inner disk.

We can scale these ideas up to AGN if the accretion flow is simply a function of radius in terms of Schwarzschild radii and mass accretion rate in terms of fraction of the Eddington rate. The disk evaporation mechanism should still work in the same way around supermassive black holes (Rozanska & Czerny 2000). Thus it seems likely that those AGN which accrete at a low fraction of the Eddington limit should also be similar to the low/hard state from galactic black holes. Conversely, AGN at high mass accretion rates (Narrow line Seyfert 1's and MCG-6-30-15 ?) are probably the counterparts of the high and very high state spectra seen in the Galactic black holes where the disk probably extends down to the last stable orbit. To test these ideas we again need some way to determine the extent of the inner disk, but as the disk temperature scales as $M^{-1/4}$ then it is even harder to observe the direct disk emission in AGN than in GBH. Reflection is then probably the best current way to track the extent of the optically thick accretion disk, and the very broad line seen in MCG-6-30-15 (Tanaka et al., 1995; Wilms et al., 2002) points to a disk which extends down to at least the last stable orbit. However, results from other AGN are currently controversial. Lubinski & Zdziarski (2001) find that AGN with harder spectra and probably lower mass accretion rates show less relativistic smearing and less reflection, consistent with the accretion picture outlined above for the galactic sources, while previous literature has stressed the similarity of the line profiles to that of MCG-6-30-15 (e.g. Nandra et al 1997). Current challenges to observers are to disentangle the shape of the line in AGN, especially those with hard spectra, so as to determine the nature of the accretion flow in low mass accretion rate AGN, and to theoreticians to develop a better understanding of the high mass accretion rate disks.

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